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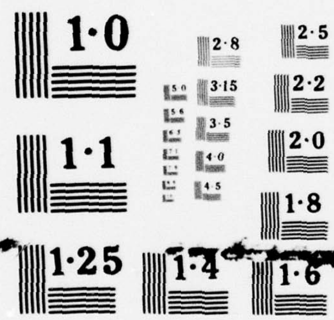

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CRITICAL EVALUATION OF LOW-ENERGY SHIP COLLISION-DAMAGE THEORIES AND DESIGN METHODOLOGIES

LEVEL

VOLUME II: LITERATURE SEARCH AND REVIEW IS

SHIP STRUCTURE COMMITTEE
1979

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Ship Structure Committee

An Interagency Advisory Committee
Dedicated to Improving the Structure of Ships

Address Correspondence to:
Secretary, Ship Structure Committee
U.S. Coast Guard Headquarters,(G-M/82)
Washington, D.C. 20590

SR-1237
APRIL 1979

Interest in structural protection from collision, grounding or stranding ranges from nuclear-powered vessel design to minor damage resulting in pollution. The interest involves economics, safety of life and property, and conservation of the environment.

In view of the existence of a body of prior research, the Ship Structure committee has conducted a project to critically evaluate this prior effort and determine whether at least one of the available design methods or a combination of methods can be used with confidence for minimization of collision damage and protection of the vessel.

This is Volume II of the final report of the project and contains the annotated bibliography. Volume I contains the analysis, results, and recommendations.

Henry H. Bell
Henry H. Bell
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-285

FINAL REPORT

on

Project SR-1237

"Collision Damage and Dtranding"

CRITICAL EVALUATION OF LOW-ENERGY SHIP COLLISION-DAMAGE THEORIES AND DESIGN METHODOLOGIES

VOLUME II: LITERATURE SEARCH AND REVIEW

by

P. R. Van Mater, Jr.
J. G. Giannotti

GIANNOTTI & BUCK ASSOCIATES, INC.

With contributions by

N. Jones and
P. Genalis

under

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16. Abstract

This report is Volume II of a two-volume report prepared under Ship Structure Committee Project SR-237, "Critical Evaluation of Low Energy Collision Damage Theories and Design Methodologies".

The material contained herein is the result of one of the tasks of the project which called for conducting a literature search and review of documents relevant to low-energy collision damage. The various data resources used were identified; the state of the art in ship collision research was summarized; an annotated bibliography of the key documents was prepared and a list of references which are considered to be relevant to the problem was developed.

Volume I contains the actual assessment of the various low-energy collision damage theories and design methodologies along with recommendations for their use and future research.

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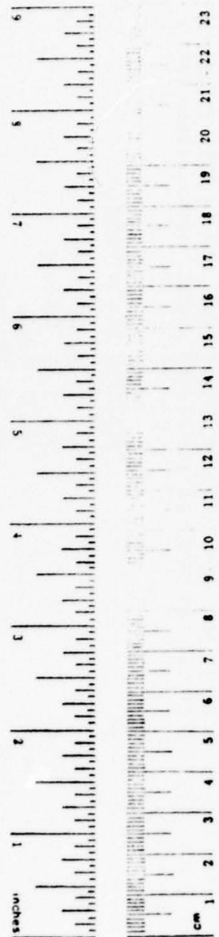
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

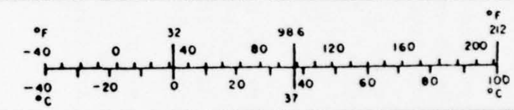
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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VOLUME II

INTRODUCTION

This report is Volume II of a two-volume report prepared under Ship Structure Committee Project SR-237, "Critical Evaluation of Low-Energy Collision-Damage Theories and Design Methodologies".

The material contained herein is the result of one of the tasks of the project which called for conducting a literature search and review of documents relevant to low-energy collision damage. The various data resources used were identified; the state-of-the-art in ship collision research was summarized; an annotated bibliography of the key documents was prepared and a list of references which are considered to be relevant to the problem was developed.

Volume I contains the actual assessment of the various low-energy collision-damage theories and design methodologies along with recommendations for their use and future research.

0 LITERATURE SEARCH AND REVIEW

A search of the pertinent U. S. and foreign literature resulted in the development of a bibliography of 428 citations. Copies of 192 documents were obtained for review and possible use as data sources for the study in question. The methods used in the search have included:

- Reference citations in technical papers and reports
- Manual search of indexes including
  - Government R&D Report Index
  - MRIS Index
  - Engineering Index
  - Oceanic Index
- Computerized search using NTIS, Lockheed DIALOG and ASDMS (Advanced Ship Data Management) Systems

Over half the citations represent various papers on structural analysis, plastic analysis, limit analysis, etc. which have been referred to in the various literature on ship structural problems. It became quite evident from the collected references that there is an abundance of literature on analytical methods for treating structural components in the plastic range, however, the literature on the synthesis of these methods to analyze the overall ship structure is much more limited. Only a few documents deal with the problem of low-energy collisions.

To suggest the availability of information, a breakdown on the documents collected is given below:

DOCUMENT TOPIC	NUMBER OF CITATIONS	DOCUMENTS HELD
Structural analysis, theory and experiment	220	93
Collisions, research and design	73	31
Collisions, low-energy analysis	6	6
Collisions, statistics	26	23
Collisions, model tests	18	5
Collisions, vehicles	10	0
Ship Structures, general	43	13
Ship Structures, ice strengthening, ice breakers	13	8
Ship Structures, slamming loads	15	11
Miscellaneous	4	2
Total	428	192

2.1 SUMMARY OF PAST AND CURRENT WORK IN SHIP COLLISION RESEARCH

Recently Professor Jones (34) wrote a survey paper on the collision protection of ships. Excerpts of this paper are included as part of this summary followed by an update of such a survey based on recent and on-going work being conducted by the Maritime Administration in cooperation with the German Government.

"Many articles have been published over the past decade on various aspects of automobile, train and bus collisions, and some of these (e.g. (55)) have demonstrated clearly the important contributions which structural plasticity can make to developments in this area. However, the complexity of an automobile or train collision, which involves many non-linear effects (e.g. large strains, strain-rate sensitive material behavior, etc.), is a serious obstacle to the further development of both theoretical and numerical procedures (58). Moreover, the response of a structure which is subjected to dynamic loads can be quite different to the behavior when the loads are applied statically, as observed in experimental investigations which have been reported in References (33) and (42) on the longitudinal impact of motor coaches. Thus, the full-scale testing of automobiles and even aircraft (e.g. (60)) has played an important role in the prediction and improvement of crashworthiness characteristics (47, etc). This is sometimes a very expensive and time-consuming procedure, a situation that has resulted in recent studies on the feasibility of scale-model experiments (31, 32) which are attractive because a systematic variation of the relevant parameters can be undertaken. However, caution must be exercised when scaling the experimental results up to full size, although Holmes and Sliter (32) did obtain encouraging agreement between the experimental behavior of scaled models and full-sized vehicles. Duffey (18) has shown that the influence of material strain-rate sensitivity cannot be properly scaled when a model and a prototype are constructed of identical materials. Further theoretical objections may well be encountered when attempting to correlate the response of models and prototypes which involve fracture.

"Lee and Wierzbicki (41) are currently utilizing Martin's theorems in dynamic plasticity in order to obtain bounds on the response of certain components in automobiles. These simple methods appear promising for the preliminary design of bumpers, doors and internal energy absorbing devices, etc.

"The foregoing comments are intended to provide a very brief overview of the many experimental and theoretical investigations which have been conducted into the crashworthiness of various land-based vehicles.

"The ship collision problem is more complicated than the automobile collision problem for a number of reasons, not least of which is the enormous amount of kinetic energy possessed by some ships on the high seas. Thus, the majority of investigations which have been published in this area were conducted on experimental models. The limitations on scaling referred to in a previous section acutely apply when scaling up the experimental results on models in order to predict the behavior of full-sized ships due in part to hydrodynamic interactions which strongly affect the end result.

"Akita and Kitamura (3) observed that the bow structure of a striking ship plays a very important role during a collision between two ships. The included stem angle, rake and framing of a bow clearly are important, but the ratio between the strength of the bow of a striking ship and the strength of the side of a struck ship has a major influence on the partition of energy exchange between the two ships. Generally speaking, a stiff bow (e.g. icebreaker) would absorb very little energy so that most of the kinetic energy lost during impact must be absorbed by the side of the struck ship. On the other hand, a weak bow may absorb most of the kinetic energy lost during a collision leaving the side of the struck ship essentially undamaged. Incidentally, Cheung has suggested a design for a soft bow in Reference (14).

"Despite the great deal of care and attention that authors have devoted to the experimental work performed in Italy (10,63), Western Germany (67 to 85), United Kingdom (96), and Japan (1-3,5-7), it was nevertheless necessary to make compromises. Some experiments have been conducted statically, or with rigid bows, while others have utilized a primitive structure for the side of a struck ship. As far as we know, all experimental investigations have examined the symmetrical case in which the striking ship impacts at right angles in the central region between two adjacent transverse bulkheads in the mid-ship section. Incidentally, Akita, et al (8) use theoretical arguments to show that this case is more severe than either eccentric or oblique collisions. However, this is not always true because McDermott, et al (46) have shown that less energy is absorbed before hull rupture when a vessel strikes near the transverse bulkhead of an oil tanker. Another aspect which has not received too much attention is the influence of added mass. Minorsky (48) assumed that the virtual increase in mass of the struck ship

due to entrained water was 0.4 times the mass of the struck ship, since previous studies on the transverse vibrations of hulls in deep water indicated that the liquid added mass was approximately this value. In fact, the theoretical results which are presented in Figure 1 of Reference (48) show that the kinetic energy lost during a collision is relatively insensitive to the actual value of the virtual mass. The largest discrepancy according to Minorsky's theory occurs when the mass of the striking ship is larger than the mass of the struck ship. For example, when the mass of the striking ship is double the mass of the struck ship, then the kinetic energy lost during a collision when the added mass is neglected is two-thirds of the value when the added mass equals the mass of the struck ship. The theoretical results for the amount of added mass recommended by Minorsky lie about mid-way between these two calculations. More recently, Akita, et al (2) conducted some experimental tests on a ship model and obtained good agreement with a simple theoretical approach which predicts the added mass during a right-angled collision. It turns out that the added mass of the model is about 40 percent of its mass when the duration of impact is short. However, the actual value of added mass depends on the duration of impact and on the functional form of the external force. In order to provide some guidelines on how short the duration of a typical collision must be in order that an added mass of 40 percent of the mass of a struck ship is appropriate, it would be worthwhile to conduct some additional tests and to properly scale them up to typical full-sized ships.

"The protective structural arrangements which have been examined in all the studies on nuclear powered ships, oil tankers and the single study on a L.N.G. (liquified natural gas) carrier (12) are similar and utilize either the normal structural designs for these vessels or a slight, modification which includes additional decks specifically designed to absorb the kinetic energy lost during a collision. However, it is clear that the design requirements for these various ships are different. Clearly, the bow of a striking ship must not be allowed to penetrate the containment vessel of a nuclear-powered ship. Presumably a similar design requirement would be used for a LNG carrier, except that a number of cargo tanks would require protection. The entire length of an oil tanker requires protection so that it is only feasible in this case to provide protection for minor collisions.

"The simple semi-analytical formula of Minorsky (48) was developed by neglecting the influence of those members which have little depth in the direction of penetration. For example, Minorsky retained the influence of decks and transverse bulkheads in the struck vessel, and decks, longitudinal bulkheads and a portion of the shell plating in the striking vessel. However, the actual energy absorbed by the struck and the striking ships was not calculated, presumably because of the difficulty in estimating the failure loads of the various structural members involved in a collision. In order to circumvent this difficulty, Minorsky introduced a resistance factor which is related to

the volume of material located in the damaged portions of the striking and struck ships. Minorsky plotted this resistance factor against the kinetic energy lost during a collision and observed that the data from a number of actual ship collisions essentially collapsed onto a straight line. The design formula developed by Minorsky (48) is in fact the equation of this straight line.

"The simple theoretical method of the Naval Construction Research Establishment (N.C.R.E.) (96) was developed for a rigid bow and only considered the influence of the deck plates and bottom of a struck ship, which were assumed to have crippling stresses which were 90 percent of the corresponding 0.3 percent proof stress. Nevertheless, Belli (10) has recently summarized the experimental work which has been conducted in Naples since 1961 and found that the N.C.R.E. method gave good predictions provided appropriate allowance was made for the rigid bow approximation.

"The design procedures due to Minorsky (48) and N.C.R.E. (96) neglect the influence of the shell plating in the struck ship and are therefore expected to be more appropriate for major collisions. In this connection it should be remarked that essentially only bending energy would be absorbed by a flat plate when it is perforated by a rigid wedge which has the same assumptions and the simple theoretical procedure given in Reference (104) for a thin plate perforated by a circular drift. However, it is quite clear that the behavior of the shell plating of oil tankers assumes vital importance during collisions if the cargo is to be contained (i.e., perforation prevented). McDermott, et al (46) have developed a structural analysis for minor tanker collisions which focuses on the behavior of the shell plating in the struck ship. It turns out that typically between 2/3 and 9/10 of the total energy absorbed during a minor collision is absorbed as membrane tension in the stiffened hull plating. However, it is remarked in Reference (105) that the strength of beams and rectangular plates are very sensitive to the magnitude of the in-plane displacements at the supports and some specific expressions are derived in Reference (35) which could be developed further to assess the importance of in-plane displacement in tanker collisions.

"Akita, et al (2) observed that there were two major types of failure in transversely framed side structures which were penetrated statically with rigid bows. A deformation type of failure occurred when the strain directly below the bow was less than about 0.3, while crack-type failures were associated with larger strains. It appears from some dynamic tests on similar structural arrangements, which were reported by Akita, et al (2), that the energy absorbing mechanisms and fracture types were similar to those observed in the corresponding static tests. However, the energy absorbed in a dynamic test was larger than that which was absorbed in the corresponding static tests, a circumstance which was attributed to the influence of material strain-rate sensitivity. It should be remarked that this increase in capacity might not be realized in a ship during a collision because this is a highly nonlinear phenomenon which is very sensitive to size. Moreover, the

influence of material strain-rate sensitivity cannot be properly scaled up from a model to a full-sized structure which is made from the same material (18). Furthermore, it appears that no investigations, except Reference (35), have been undertaken to examine whether the structural response of ships may be considered to be static, or whether it is necessary to retain the influence of inertia forces. It was suggested in Reference (106) that the structural response of a panel in a marine vehicle during a severe slam could be accurately predicted with a static analysis, provided the duration of the pressure pulse is longer than the fundamental period of elastic vibration. Indeed, encouraging agreement was obtained between the theoretical predictions according to a static analysis and some experimental results which were recorded on a one-quarter scale model of a section of the bottom of a U. S. Coast Guard cutter. However, the inertia terms must be retained when the duration of a pressure pulse is short. It was shown in Reference (35) that the structural response of the shell plating of the particular tanker design considered in Reference (46) could be predicted with sufficient accuracy using a static analysis. It would therefore appear worthwhile to develop further these simple ideas in order to provide guidelines which indicate when static analysis could be used with no sacrifice in accuracy, although it is likely that the retention of inertia terms would be unavoidable when analyzing even minor collisions of high-speed marine vehicles.

"Akita, et al (2) and Arita (7) have developed approximate theoretical procedures which consider the energy absorbed in the shell plating, as well as various other members for both the deformation and crack failure modes which occur during ship collisions. These theoretical predictions agree reasonably well with some experimental results recorded on idealized models which are reported in Reference (2) and are further discussed in References (12) and (95). It appears that these theoretical analyses should bridge the gap between the analysis of McDermott, et al (46) for minor collisions in which the membrane energy of the shell plating is dominant and the analyses of Minorsky (48) and N.C.R.E. (96) for major collisions in which the membrane tension in the shell plating of the struck ship is neglected. However, there are a large number of different assumptions in these various analyses so that the theoretical methods in References (2) and (7) do not agree with each other and appear to neither reduce to Reference (46) for minor collisions nor to References (48) or (96) for major collisions.

"It should be remarked at this juncture that relatively little is known about the fracture of structural members which are subjected to large dynamic loads. Apparently, the only investigation which is relevant to ship collisions, is the experimental study on beams by Menkes and Opat (107) and the subsequent theoretical analysis of the same problem which appears in Reference (108). It is clear that much further work is required on the fracture

of rectangular plates and grillages as well as in the effects of size before the theoretical procedures of References (2) and (7) and others can be used with confidence for parameters which do not lie within those of the experimental tests. Indeed, it is not anticipated that a theoretical method will be developed in the near future which can predict accurately the structural response during a collision between two ships. The chief virtue of the various available theoretical methods is that they allow a comparison of various designs and suggest the most favorable collision protection arrangements."

Current work in structural response of colliding ships is being conducted by Genalis, Minorsky, and through a contract, by Hydronautics senior analysts. Of primary concern is the estimation of loads which occur at impact, their duration, their magnitude, distribution and area of application. Previous work is being evaluated and new techniques are being considered. For example, Faulkner's work (22) is being applied. These loads will then be utilized in the numerical analysis of several structural configurations using sophisticated finite-element computer programs Partially due to high cost of such analyses, a comprehensive study of available numerical analyses techniques is being carried out to establish the most suitable one.

Simultaneously, a longer range plan is pursued where a collision synthesis model will be produced based on the individual behavior of structural components and the statistics of overall structure behavior.

2.2 U. S. AND FOREIGN DATA SOURCES

2.2.1 United States

A. M. Rosenblatt & Son/U. S. Steel (1971-1975)

A series of studies were conducted, sponsored by the U. S. Coast Guard intended to develop a methodology for the analysis of minor collisions. In addition a number of collision inspection reports are available. See References 46, 102, 103.

B. MARAD (Current)

Under MARAD sponsorship George G. Sharp, Inc. is using methods developed by Professor Reckling (University of Berlin) to predict forces observed in GKSS collision experiments. In a parallel MARAD funded effort, Hydronautics, Inc. has developed a finite-element model of the GKSS energy resisting barrier to predict the elastoplastic response to "known" input dynamic loads. See References 49 thru 53.

C. Gibbs & Cox, Inc. Design Manual

At the time of the design of the N. S. SAVANNAH in the late 1950's by George G. Sharp, Inc. an independent study at Gibbs & Cox, Inc. was funded by MARAD. The product of this study was a design criteria manual for nuclear-powered ships. See Reference 109.

D. U. S. Coast Guard Casualty Reports

These are reports of all collisions which either involve vessels of U. S. registry or occur in U. S. water. The reports are maintained by the U. S. Coast Guard Office of Merchant Marine Safety.

E. U. S. Naval Safety Center (Norfolk, Virginia)

This office maintains records of all collisions involving U. S. Navy vessels.

F. Massachusetts Institute of Technology, Department of Ocean Engineering

At the present time the Department of Ocean Engineering of M.I.T. has a contract from the Ship Structure Committee to gather and monitor R&D work in the area of ship collision damage both in the U. S. and abroad. The SSC project title is "Surveillance of Ship Collision/Stranding Research Studies" (SR-1246). The Principal Investigator is Professor Norman Jones.

G. University of Rhode Island, Department of Ocean Engineering

N.M.R.C. sponsored a graduate research project at the Department of Ocean Engineering of the University of Rhode Island. Model tests simulating ship collisions were conducted in the elastic range. Accelerations and velocities were measured at two points. Impact occurred on transverse steel bulkhead. An added mass coefficient of 0.39 was inferred. See Reference 110.

2.2.2 Germany

Under the supervision of the Geselischaft fur Kernenergigiever Wertung in Schiffbau und Schiffahrt (GKSS), Geesthacht-Tesperhude, a series of dynamic collision tests were conducted from 1967 to 1975. Three of the tests were conducted with absorption barriers of the OTTO HAHN type, nine tests with resistant barriers with various bow configurations. The latter fall within the low-energy collision definition

(no shell rupture). Investigators in these efforts are Mr. G. Woisin and Dr. Letnin of GKSS and Professor Reckling of the University of Berlin. See References 67 through 86.

2.2.3 Japan

Dr. Y. Akita of the Japanese Classification Society has reported on collision research in Japan. Interest in the problem, as in the case of GKSS, stemmed from interest in nuclear powered ships as far back as 1958. Experiments were conducted as early as 1963 with the greatest activity occurring during the 1966-1969 time frame. See References 1-3, 5-7, 54, 59, 66.

2.2.4 Italy

During the mid 1960's the Italians, principally under the direction of Professor F. Spinelli of the University of Naples conducted a total of 24 tests on collisions of various configurations. Test results have been reported together with an analytical treatment. See References 10, 61-65.

2.3 ANNOTATED BIBLIOGRAPHY

This section gives brief summaries of those documents which were considered to be key sources of information for the study on low-energy collisions. A number of the summaries presented are based on those given in the following two reports which describe the state-of-the-art up to the time they were written. These are:

(a) "Tanker Structural Evaluation," M. Rosenblatt & Son, Inc., Report No. 2087 prepared for the Department of Transportation, U. S. Coast Guard under Contract DOT-CG-10,605A, April 1972.

(b) "Report on Ship Collision Study, Present Situation Survey," George G. Sharp, Inc., Report 5516 prepared for Babcock & Wilcox Company and the U. S. Maritime Administration, November 1975.

Additional summaries are presented to cover key publications written since the time the above two documents were published and to include other older documents which are relevant.

1. Preliminary Analysis of Tanker Collisions and Groundings
U.S.C.G. Office of Research & Development - Project 713112, by David M. Bovet, January 1973.

This report presents the results (of 51 collisions and 13 groundings) of a preliminary analysis of tanker collision and grounding data. Statistics are presented for the geographical location of collision. Collisions are analyzed in terms of

vessel size, vessel speed at time of occurrence, angle of collision, depth of penetration and geographical location. Correlations of penetration depth with striking ship speed, momentum, and energy are attempted. A brief analysis of tanker groundings is presented. Diagrams are given, and a computer analysis program is exhibited.

The sample used is small and the size of struck vessels is also limited. A large percentage were struck beam on and a high percentage of collisions were in harbors or approaches. The method needs extension with more data and a broader range of vessels.

2. Tanker Structural Analysis for Minor Collision, by J. McDermott, R. Kline, E. L. Jones, N. Maniar and W. P. Chiang, SNAME, 1974.

Mathematical models and experiments were studied for bending and buckling followed by membrane stretching with and without web frame failure up to hull rupture. Both single and double skinned ships are studied.

It is shown that for minor collisions membrane tension provides a large part of the energy absorption. Comparative values are given in tabular form for impacts at different points of the span between web frames.

Even though the paper attempts to simplify the problem by hedging it in by numerous assumptions, one gets the definite impression that it is difficult to contain the problem within bounds: the degree of restraint exerted by web frames on the supported panel is not obvious, the support provided by the inner hull of a double hull ship would seem to depend on web spacing, depth of cofferdam and waterplane angle of striking bow, which is not brought out. The allowable penetration and effective resistance to rupture is a function of strike location in the plan view (with respect to webs) and in elevation (with respect to decks); this is not very clearly brought out. The authors conclude that the method followed does not lend itself to becoming a design tool. The paper treats only the first instant of a major collision.

3. Ship Collisions at Varying Angles of Incidence, Report No. N.C.R.C./N. 163, by F. H. Haywood, Naval Construction Research Establishment, St. Leonard's Hill, Dunfermline, Fife, February 1964.

The paper presents the results of a mathematical analysis of the energy absorbed in an inelastic collision for given initial velocities and masses at various angles of collision. The formulae used are developed and discussed. The results are presented in graphical form and indicate that:

A. For collisions amidship, and if the displacements of the two ships are nearly equal, maximum energy absorption occurs at a collision angle of:

   (i) 90^o when the struck ship has zero initial velocity.
   (ii) 160^o to 180^o when the struck ship has an initial velocity in the range of one half to double the velocity of the striking ship.

B. For collisions at bow or stern of struck ship, if the displacements of the two ships are nearly equal, the maximum energy absorption occurs at a collision angle of approximately 180^o regardless of the relative masses of the two ships.

C. For collisions at bow or stern of the struck ship, the maximum values of rotational energy absorption for all combinations of ship speeds occur at collision angles ranging between 70^o and 90^o and is at the maximum when the struck ship has zero initial speed.

D. For amidship collisions, the energy absorbed is maximum at collision angles ranging between 160^o and 180^o and increases with velocity of the struck ship.

This paper presents a convenient tool for evaluating the relative energy in ship collisions for various combinations of ship weight, collision course and point of impact on the struck ship. Assuming the mathematical method of analysis presented can be verified by spot check experimental results, this paper offers a simple inexpensive method of establishing an optimum model test program.

After completion of the model tests the formulae presented in this paper could be calibrated to provide a convenient method of comparing and evaluating intermediate combinations of ship weights, collision courses and relative velocities not covered by the model tests.

4. A Theoretical Note on Ships Collisions, by J. H. Haywood, Report No. R.445, Naval Research Establishment, St. Leonard's Hill, Dunfermline, Fife, February 1961.

A ship collision is analyzed theoretically in the case of a ship striking a stationary ship amidship and at right angles. Calculations are carried out assuming the collision force is either constant or varies linearly with depth of penetration. The total work done, collision force, penetration, duration of collision, and energy partition are examined including the energy absorbed by transverse vibration of the ship as a beam.

This paper may be the only one trying to solve the equations of motions, which are greatly simplified by limiting the solution to a particular case. The solution and the conclusions from the investigation is applicable only to the cases of direct, central, and symmetrical impact. Since the reactor compartment is usually near the stern, some of the conclusions do not apply. Also treating the ship's hull as a uniform beam is not realistic. Even though this paper is still too simple to be practical, it is much better than the approach by Castagneto and the others.

Haywood's conclusion about zero collision force and zero work done is not practical. This conclusion is obtained only because he has used the constant force assumption. According to all experiments the force at small duration is mostly linear and then becomes more or less constant. Practically, ships involved in collisions never behave like perfectly elastic rigid bodies.

5. An Analysis of Ship Collisions with Reference to Protection of Nuclear Power Plants, by V. U. Minorsky, Journal of Ship Research, October 1959.

Ship collisions are assumed to be almost wholly inelastic. A relationship for kinetic energy lost in the collision is developed based on ship displacements, speed V_B of striking ship and "added mass of water" assumed to be .40 that of struck ship.

An empirical linear relationship was found to exist for high-energy collisions between lost kinetic energy and a "resistance factor" R_T which includes the volume of structural members which are edge-on to direction of collision, such as decks, flats, etc. in both ships, longitudinal bulkheads of striking vessel, and a component of striking vessel shell taken at .70 of shell area 5 ft. deep in way of deck.

An allowance of one-third increase in R_T is made for the forward speed of struck vessel.

The method allows an approximate calculation of depth of penetration into ships of conventional design, or of the "critical speed" for which a known bow will reach a certain penetration into a given ship side.

It is implicit that the collision occurs approximately at midships where the energy spent in the collision and hence the penetration are at a maximum value.

This easily applied approximate method is useful in the case of collisions involving conventional ships where collision protection is of the absorbent type.

6. Collision Problems for Nuclear Ships, by G. Woisin, Hansa 1964, No. 10.

This paper is a review of the state of knowledge of the subject (1964) covering the dynamics of collision including research on added mass, a discussion of the SAVANNAH collision analysis and the energy spent in elastic deformation. A review is made of all of the experimental work and of the various collision protections schemes. Much of this material is covered in other papers by the same author.

There is little that is new in this paper but it has value as an overview of the subject at the time it was written.

7. Collision Considerations in the Design and Construction of the "SAVANNAH", by J. A. Dodd & S. MacDonald, Motor Ship, November 1960.

The paper reviews the SAVANNAH's characteristics, containment vessel support and scantlings, shielding and collision protection including the method of calculating critical speed.

The paper is a convenient summary but does not add anything new.

8. Estimating the Decelerations Sustained in Ship Collisions, by G. Woisin, Schiff und Hafen 13 (1961) November.

The author discusses the importance of establishing the deceleration (also acceleration) of ships in a collision and indicates it can be calculated simply if the total penetration is known from the speeds and masses using the relationship established in the SAVANNAH study, with and without the resistance of the water. He also examines the extreme case of a ship ramming a rigid quay wall. Finally, he calculates the duration of the deceleration using a graphical method.

The author states that the calculated decelerations are too high, approximate and uncertain. It would appear that relationships between penetration and time for given vessels would be better obtained from tests.

9. Research on the Collision Resisting Construction of the Sides of a Nuclear-Powered Ship, (Report No. 3) by H. Ol, T. Harima, H. Iizuka and G. Kataoka, Mitsubishi Nippon Heavy Industries Tech. Review .4 (1963).

Loads were applied by a swinging weight, also statically by a screw jack to ship side models built to a 1/15 scale. Models were of two types, S1 with 3 decks and transverse framing, and S2 with 2 decks and additional frames and longitudinal stringers. Several types of bows were used including B1 simulating a rigid bow. In some experiments (Group 1) only the side model was deformed; in others (Group 2) only the bow, and in Group 3

both bow and side models were deformed. Relationships were developed between energy absorption and structural deformation. The following were measured or investigated:

1. Velocity of bow model and deformation of side model.
2. Load
3. Local strains (by means of strain gage)
4. High-speed camera pictures of destructive process.
5. Final configurations of models after experiments were completed. (Extent of damage).

The results were:

1. If both bow and side are destructible, the load - deformation relation for each is almost the same as for collision of bow with a rigid wall or of the side with a rigid bow.
2. The maximum load on a bow colliding with a rigid wall is the maximum load on the bow shell panel forward enclosed by decks and frames.
3. There is an optimum thickness for shell plating which depends on several variables.
4. When bow is stronger than side shell, the energy is absorbed almost entirely by the side structure.

The derivation of equations is not obvious and the theory does not seem easy to apply, but useful work is reported.

10. <u>Research on the Collision - Resisting Construction of the Sides of a Nuclear - Powered Ship</u>, Report No. 2 by T. Harima, S. Yamada and Y. Tokuda, Mitsubishi Nippon Heavy Industries Technical Review 2, 1961.

The paper gives test results for the impact resistance of beams, flat plates and stiffened plates. The effects of strain hardening, strain speed and variation in yield stress are studied.

Some of the results are:

1. Absorbed energy = Plastic moment x Bend angle
2. Load-deflection relationship for simple plate fixed at both ends can be calculated considering tensile stress only in the axial direction; with stiffened plate the calculation must include the bending stress too.
3. The load deflection relationship can be calculated taking the simple square plate as a circular membrane and the stiffened square plate as a grid.
4. The above calculations must take into consideration, strain speed and strain hardening as variable coefficients.
5. Absorbed energy per unit deflection favors HT over MS, but energy to rupture favors MS over HT.

11. Equivalent Added Mass of Ships in Collision, by S. Motora, M. Fujino, M. Sugiura & M. Sugita, JSNA, December 1969.

The authors have calculated and verified by experiments that the added mass of the ship which is .40 at first is not constant but varies during the collision, increasing with duration of impact. They calculate the acceleration at the end of the collision dividing the external force by an equivalent added mass.

The highest values of added mass are for the case of a soft-structured ship struck at low speeds with a considerable amount of penetration. In the case of a ship with strong collision protection struck at high speed with relatively low penetration, the added mass is very close to the .40 assumed for the N.S. SAVANNAH.

12. Model Testing with Collision Protection Structures in Reactor Ships, by G. Woisin, Schiff und Hafen, July, 1972.

The author states that he is concerned only with dynamic tests, with only slightly simplified models. He is not concerned here with the influence of the water surrounding two ships in collision. The test stand is described, followed by a discussion of scale effects.

It seems questionable to state that successively greater impacts on the same model can be produced without incurring a strain hardening effect different from that which would be produced for a maximum impact. There is no clue to the brittleness scale effect.

13. A Study on Collision of an Elastic Stem with the Side Structure of a Nuclear Ship, by Yoshio Akita & Katsuhide Kitamura, B.S.R.A. No. 35300, Soc. of Nav. Arch. in Japan, 1972.

Collisions test results of 1/10 scale models are compared with calculated values, using the Minorsky method. Tests of one model of hull side structure of the struck vessel were made in conjunction with six (6) bow models of the striking ship featuring variations in framing and scantlings. Two of the bow models were transversely framed and four (4) were longitudinally framed. The six (6) bows were graded from soft to hard based on their ability to resist deformation in a collision. The transversely framed models were on the "soft" end of the scale, and the longitudinally framed with heavy scantlings was at the "hard" end.

The portion of the collision energy absorbed by the "side" and the "bow" models is measured and compared with theoretical values calculated by the Minorsky method.

This paper presents information on model test results and concepts having direct application and/or provides guidance on the design of a suitable protective structure in way of the reactor.

14. A Study of Similarity Laws of Impact Damage, in Particular of Ship Collisions and Collision Model Tests, by G. Woisin, Schiff und Hafen 20, 1968.

Laws governing similitude are listed and it is brought out that it is desirable to satisfy Kick's law concerning stresses and strains as well to have equal strain velocities; at the same time, if the impact is sudden, there are inertia forces to consider which introduce a Newtonian dynamic similarity; however, for the forces exerted on water, the liquid being the same for ship and model, viscosity forces are the same, and so are gravity forces. All this leads to the conclusion that not all conditions can be met by one set of similitude laws. The author goes on to explain that some of the relationships can be neglected as being of little significance. Some of the considerations that cannot be neglected are:

1. Temperature (brittle fracture)
2. Strain hardening
3. Molecular structure

These will introduce scale effects.

Empirical formulae are given that reconcile full-scale results with model tests to various scales and a corrected "similarity law" for tests in the dry is developed.

The author proposes that similarity laws be verified comparing ships, statistically similar cases, and models, so as to refine the relationship taking into account various scale effects.

It is pointed out that at small scales more energy must be applied--as much as 110% more at 1/15 scale than for full scale--because of strain hardening.

Experimental verification of many of the relationships presented is missing. It is suggested that well-known case histories and statistical data be applied to:

1. Actual ships
2. Partly ships, and partly models
3. Model tests

The difference due to strain hardening alone at scales of 1/7.5 and 1/15 instead of $(1/2)^3 = 1/8 = 0.125$ is about 38% higher or 0.174. The difference between full scale and 1/15 scale is about 110%.

15. Analysis of World Merchant Ship Losses, by W. J. Beer, RINA, March 28, 1968

A general statistical summary of various types of ship losses of vessels insured by Lloyds over the period 1949 thru 1966, grouped by ship size for both tankers and general cargo ships. The losses are categorized as follows:

1. Wrecked
2. Foundered
3. Collision
4. Burnt

This paper provides a broad general picture of the causes of ship losses over the period of 1949 - 1966 but contains little technical data applicable to collision analysis.

16. The Distribution of Collisions in Japan and Methods of Estimating Collision Damage, by Yahei Fujii and Hiroyuki Yamanouchi, B.S.R.A. No. 35,299.

Presents data on all recorded collisions along the coastline of Japan during the period 1966 - 1968. The data is categorized by ship size and by location of collision; i.e., in harbors and outside of harbors. The latter category is further subdivided into several major coastal areas.

The statistics presented in this paper indicate that most of the collisions in Japanese waters involve small vessels of under 500 tons. No attempt is made to correlate the collisions with their probable cause other than to grade them by ship size and geographic location, as noted above. However, the paper presents a rather sophisticated mathematical procedure by which existing collision statistics could be adjusted for variations in ship size, traffic density, etc.

17. Research on the Collision Resisting Construction of the Sides of a Nuclear Powered Ship, by Kagami, et al, Mitsubishi Nippon Heavy Industries Technical Review, Fol. 2, No. 1, 1961.

Models to 1/20 scale of a 45,000 DWT tanker with nine (9) different side structures were hit by a pendulum simulating the bow of a 45,000 DWT tanker at 5 knots. Results were compared qualitatively for damage depth, stresses and impact forces developed.

The experimenters conclude that the side shell should be made much stronger than the striking bow, that the reactor wall and the side shell should not be structurally connected, that a grid is the best stiffening for the side plating, and that it is effective to increase the side plating thickness.

The tests do not include any variation in kinetic energy; the kinetic energy is quite low. Some of the configurations are of no interest. The experimenters in their conclusions overlooked the significance of the very high impact forces of test T1 and the corresponding acceleration from the standpoint of the reactor control rod design.

18. Destructive Energy in Ship Collisions, by E. Castagneto, Technica Italiana 27, No. 10, December 1962.

Formulae are developed to obtain the energy developed at impact, both direct and off center, showing the advantage of placing the reactor aft. Also the proportion of energy spent in elastic deformation of the hull is studied as well as the relative strength of anti-collision structures. The added mass of water is discussed and experimental results are presented.

These results were:

1. Experiments are advisable to determine added mass of water in the case of ships other than tankers.
2. The energy lost in elastic deformation is small (less than 5% of total).
3. The strength of collision protection should not be so great that the collision will cause excessive stresses in the hull.
4. Off-center impacts produce less energy loss than impacts at the c.g. of struck ship and it is preferable to place the reactor at the stern.

19. Studies on Collision Protective Structures of Nuclear Powered Ships, by Y. Akita and 3d Nuclear Ship Research Committee. Shipbuilding Research Association of Japan Report No. 71.

This paper is a summary of all Japanese research work on collisions between 1966 and 1970, representing work by 13 panels combining private industry and government organizations. A large part of the work consists of attempting to derive equations, based on theory and experiment, with which to analyze collisions. Other subjects investigated deal with the added mass of water, distribution of absorbed energy in a collision as a function of relative stem-side shell strength, stem angle and collision angle variation and the relative strength of various side structures.

This paper represents the results of a good deal of useful experimental work. The so-called deformation-type fracture is of interest only at the lower end of the energy scale; once the shell is ruptured, it cannot contribute very much, if anything. The calculation of the deformation fracture energy is difficult and somewhat doubtful as to the results.

20. Protection of Nuclear Reactor Compartments Against Collision - Results of Tests on Models, BSRA Translation No. 1827, by Franco Spinelli.

Tests were conducted using a model configured as the bow of a striking ship which ran down an inclined railway and struck the side of another model. The models were 1:15 scale representations of a typical 45,000 DWT tanker. Attached to the struck model were flat plates immersed in water in an attempt to simulate the added mass effect.

While the accuracy of its added mass aspects of the experiment are the subject of some controversy, the measured energy losses are useful in predicting the plastic energy absorption in actual tanker collisions and in correlating theoretical predictions of damage with the actual measured values. In fact, by scaling the actual deformation contours presented in the paper it is possible to obtain a rough correlation with the analytical results presented in this Tanker Structural Evaluation.

The following are representative results from the Spinelli report:

Test No.	Comparable Plastic Energy Absorption in Actual 45,000 DWT Tankers, ft-lb	Damage Occurring in Model
1	26×10^6	Four web frames grossly distorted, some bulkhead crushing, hull plate and horizontal stiffeners are bent in but not ruptured.
2	128×10^6	Damage as in Test No. 1, except that all horizontal stiffeners are ruptured and the hull plate is ruptured near the bottom.
3	230×10^6	Damage as in Test No. 1, except that all horizontal stiffeners are ruptured and the hull plate is ruptured near the bottom.

21. Strength of Huge Tankers in Collision, by Toshiro Suhara, et al, Journal of Society of Naval Architects of Japan, Vol. 128, 1970.

This paper reports the results of static penetrating tests using 1/15-scale tanker models. The model of the struck ship was a portion of the wing tank of a 400,000-ton tanker. The model of the striking ship was the bow of a 100,000-ton tanker. Two solid bow models were used, one was a normal bulbous bow stem, the other was a vertical stem with wedge-shaped cross section. Damage patterns were observed during the static penetration of the bow into the wing tank, and load penetration charts were obtained.

The experiments showed that a deck strut and its adjoining structural members such as shell plate, transverse wing, and horizontal girder which withstand the collapse of the strut provide the largest portion of the total resistance force against penetration. By assuming that a strut and its adjoining members maintain constant resistive force after buckling, an approximate method of calculating the load versus penetration was obtained. This approximate method of calculated energy absorbed was about 10% less than that measured during the experiment.

The total energy available in the testing machine was less than that necessary for collapsing the model when the vertical stem wedge was used. A gas cut about 5 feet long was made in the shell to initiate failure. The profile of the bulbous bow was such that the stem at the main deck punched through the shell of the struck ship first and the bulb provided a concentrated load which initiated local failure. In neither test was the total potential membrane tension plastic energy in the stiffened side obtained - in the vertical stem case as a result of the gas-cut, and in the bulbous bow case as a result of the punching action.

22. The Probability of Vessel Collisions, by T. MacDuff, Ocean Industry, September 1974.

Based on Channel width and stopping distances in the case for groundings in the Straits of Dover, and on ship speed, mean spacing, length and angle to stream in the case of collisions, the author develops the mathematical probability of random groundings and collisions, i.e. without the benefit of any navigational aids. He then compares these with the actual frequency of groundings/collisions, and ascribes the difference to "causation probability". He goes on to apply this concept to the possible collision of a ship with a North Sea platform.

23. <u>The Safety of the Nuclear Reactor on Merchant Ships</u>, by Franco Spinelli, Tecnica Italiana, pp. 797-812, 1963, Technica Navale.

Relative to a scale-model study of ship crash phenomena, a table of scaling laws was prepared, based on the velocities and pressures being the same in the model and the prototype. The ratio of the prototype energy to the model energy was considered proportional to the cube of the dimension ratio; the dimension ratio was assumed to be the same in any direction.

24. <u>Criteria for Guidance in the Design of Nuclear Powered Merchant Ships</u>, by Gibbs & Cox, Inc, prepared for the Office of Research and Development, Maritime Administration.

This 3-volume paper treats virtually all aspects of ship design which may be considered unique to a nuclear-powered ship. Section 4 on "Collision Barrier" is relevant to the subject of this project. It covers the following:

i. Probability of ship penetrating a collision barrier
ii. Design of absorbent, resistant and combination collision barrier
iii. Mechanics of collision
iv. Model test of simple wood absorbent collision barrier
v. Energy absorbing characteristics of conventional ship's structure
vi. Calculation of the force required to crush the bow of a Mariner class ship

Under (i) the paper provides large quantities of statistical data on collisions. Based on certain selected data it suggests a method for determining the number of collisions per year in which a container would be penetrated and the criteria for designing an absorbent collision barrier.

Under (ii) the paper outlines the approach to the design of an absorbent barrier with particular emphasis on wood, laminated steel and wood, and steel barriers resembling conventional ship structure. It also discusses design of resistant-type barriers, however, it recognizes the lack of much essential data which could result in developing an overly conservative design.

Under (iii) the paper develops an equation for the total energy transfer in collision. It reasons that it is possible to analyze the collision on the basis of an inelastic collision in a frictionless medium. In a numerical example the mass of the struck

vessel is doubled to account for entrained water while no increase is made to the mass of the striking vessel for the entrained water.

With respect to steel structures, Gibbs & Cox state that "The use of steel structures to absorb energy by collapsing and rupturing is a possibility. However, it has not been possible to find a reliable rational approach to calculating the energy absorbing characteristics of even relatively simple steel structures. (This appendix) reports an analysis of collisions between conventional ships and an attempt to obtain a correlation between volume of steel structure demolished and energy absorbed. Various other correlations with energy absorption were attempted but none appeared superior to metal volume."

The force required to crush the bow of a Mariner is calculated assuming (1), the bow acts as a column in collapsing and (2), the bow plating and stiffener collapse. The force values reported are 25,000 tons and 19,000 tons.

It should be pointed out that the statistical data on the world fleet of ships and collisions data used by Gibbs & Cox is outdated. Gibbs & Cox data is mostly pre-1958 when the ships were relatively smaller and slower.

25. Collision Protection of Nuclear Ships - A Survey of the State of the Art, by Odo Krappinger, University of Michigan, College of Engineering, May 1966.

The paper surveys significant literature published since design of the N. S. SAVANNAH and concludes that only modest progress has been made in the field of collision protection of nuclear power plants. The paper attempts to organize the problem of collision protection, however, its treatment is uneven, and some major aspects are given only cursory coverage. While there is no new information presented herein, this paper is a helpful summary for those looking for an introduction to the problem.

26. A Scale-Model Study of Crash Energy Dissipating Vehicle Structures, by G. C. Kao and G. C. Chan, Wyle Laboratories - Research Staff, Huntsville, Alabama, March 1968.

Relative to a scale-model study of vehicle crash phenomena, a "table of gravity scaling laws" was prepared, based on acceleration, modulus of elasticity, stress, and strain being the same in the model and the prototype. The ratio of the prototype energy to the model energy was considered proportional to the square of the dimension ratio; the dimension ratio was assumed to be the same in any direction. This assumption for energy scaling is compatible with membrane-force energy, rather than bending energy.

27. Tanker Structural Evaluation, by M. Rosenblatt & Son, Inc. Contract No. DOT-CG-10,605A, April 1972.

The purpose of this study was to examine existing tanker structural arrangements, determine those design features which have a significant influence on cargo protection, and provide the Coast Guard with a means of evaluating the relative effectiveness of various systems in preventing leakage after collision.

A review of pertinent literature and collision histories was conducted; boundary considerations were established; and analytic procedures were developed which provide for an assessment of the plastic as well as elastic energy absorbed in a minor collision with an unyielding ship's bow.

Seven collision cases were studied. The striking ship was a T-2 type with an unyielding bow with either 15^{o} stem rake or a vertical stem. The struck ship was a version of a 120,000-DWT tanker varied to include changes in shell material, changes in scantlings, variations in hit location, and single versus double hulls.

The analytical procedures developed in this study are for estimating the plastic and elastic energy absorbed by the structure of a conventional longitudinally framed tanker struck at its center of gravity in a right angle encounter with an unyielding bow having a vertical stem or a stem rake of 15^{o}. The following conclusions are drawn based on the application of this procedure to minor collision cases (i.e., where the collision will cause oil leakage) in which a 120,000-DWT tanker and its variations are struck by a T-2 type tanker. It should be noted that the conclusions drawn relative to double-hull ships are based on two simple hulls without the employment of any special energy absorbing material located between them as the use of special interconnecting systems such as honeycombed structure.

1. The procedure is effective in ranking tanker structure from the viewpoint of cargo containment protection afforded in the event of minor collisions.
2. Collision energy absorbed in elastic deformations of overall ship structure will be negligible for practical collision situations. For elastic energy absorption to become significant, the struck ship must have exceptionally strong side structure, so that high collision forces are generated and the striking ship is brought to rest in a period of time substantially shorter than the fundamental period of transverse vibration of the ship.
3. Single-hull ships are more efficient absorbers of collision energy than double-hull ships. The double hull is superior to the single hull in the case of a punching or tearing action where little energy is absorbed and the inner hull may remain intact and prevent leakage.

4. The most efficient way to increase the ability to absorb collision energy is to increase the thickness of shell plating. If a double hull is desired, the most efficient placement of material is to make the outer hull as heavy as possible and make the inner hull as light as possible consistent with hydrostatic and other design requirements.
5. The spacing required to insure interaction of the two shell plating systems in the double-hull case is so small as to be impractical from a construction standpoint. This does not take into account the possible use of such unorthodox systems as honeycombed structure.
6. The shape of the bow of the striking ship has a significant influence on the energy absorbed. The greater the vertical extent of side shell which can be engaged, the greater the energy required for failure.
7. The effect of ambient temperature on rupture is significant since no plastic energy can be assigned where the temperature is below the transition temperature.
8. Although there may be a large relative increase in energy absorption possible through increases in shell thickness and strength, the collision energy absorbed before rupture by conventional tanker structure is quite small. Within the collision cases examined, a T-2 at 20,000 tons displacement and a speed of 3 knots would rupture the structural configuration absorbing the largest amount of energy. Therefore, tankers of the same size are not likely to vary in their cargo containment capability after collision unless radical increases in hull weight are accepted or unless innovative non-structural containment systems are used.

28. On the Collision Protection of Ships, by N. Jones, International Seminar on: Extreme Load Conditions and Limit Analysis Procedures for Structural Reactor Safeguards and Containment Structures, Berlin, 1975.

This article provides a brief survey on the literature available on the collision protection of ships. It starts off with a brief discussion of the current state of knowledge on the collision protection of land-based vehicles. It then reviews the experimental and theoretical investigations dealing with the collision protection of various types of ships. Various energy absorbing methods are then discussed with the emphasis placed on their suitability for the protection of ships involved in collisions. The behavior of the honeycomb (hexagonal cell) structures is then investigated in some detail. Finally, alternate structural arrangements in ships which utilize hazardous energy-absorbing systems are suggested.

From this report, it appears that honeycomb structures provide a feasible alternative to deck structures which are presently used to achieve protection of ships in collisions. The feature of the honeycomb panels are explored in various ways. A design

which utilizes both sides of the hull is proposed for a nuclear-powered ship involved in a collision. In some circumstances, a nest of tubes might be advantageous over the honeycomb panels, therefore this idea is described and its energy-absorption properties examined. It is suggested that the honeycomb panels or the nest of tubes could be used in conjunction with current designs to provide additional protection.

It is also recommended that supporting experimental evidence on structural characteristics be obtained before using the designs in a ship or marine vehicle.

29. Ship Casualty Analysis, by V. U. Minorsky, George G. Sharp, Inc. November 1975.

127 monthly casualty return sheets 1964 - 1974 from the Liverpool Underwriters Association were analyzed for ships over 2,000 gross tons. Casualties were studied world wide, with special interest in casualties deriving from collisions and more specifically for those along proposed nuclear ship routes.

It was found that collisions and groundings remained constant for this period while world fleet increased. In the period there were 831 ships in collision, 850 groundings and 977 fires.

30. Development of a Collision Protection Structure for Nuclear Powered Ship, by G. Woisin, Institut fur Anlagentechnik.

Recently, nuclear containership studies were carried out with containerships having a small breadth. Because of this, the collision barrier for the reactor compartment changed from the energy-absorbing type to a resisting type. The former type consisted mainly of decks extending at least 1/5 the ship's breadth into the ship's sides. The resisting type consisted largely of grillages fitted to the inner frame of the outer shell of the ship extending to only 1/12 of the ship's breadth. The new design was tested with 8 model exponents with the same model testing facility of GKSS.

The tests showed that adequate protection against collision could be demonstrated by the resistance type barrier, Type 2 (18 mm thick web plate). Because of the very minor penetration depth protection can be achieved by carrying the grillage structure from the outer shell to a longitudinal wing bulkhead located approximately .07 B inboard rather than the .2 B minimum safety distance required for energy absorption type barriers.

31. The Collision Tests of GKSS, by G. Woisin, Geesthacht

This paper describes the GKSS collision tests in which ship bow models were impacted against ship side shell models. Three

tests were made using side-shell models with barriers of the energy-absorbing type. Nine tests were made with side-shell models of the energy-resisting type. Various bow configurations were used. The side-shell models were fixed to an encastered beam whose elastic properties simulated those of a ship. The report describes the applicable scaling laws, the test technique, the mechanics of the collision process and the results of the tests.

The tests showed that it is possible to design an energy-resistant type barrier which can successfully resist virtually any conceivable collision by constructing an "egg-carton" grillage structure between the shell and the protected compartment, in this case a reactor compartment. The tests demonstrated that when a resistant-type barrier may be reduced from .2B, required for energy-absorbing barriers, to .08B. Thus the width of the compartment protected, whether it be dedicated to cargo or a reactor is increased by 40% from .60B to .84B. Furthermore the barrier compartments could be used for carrying liquids.

The report also asserts that a further advantage of this type of construction is the watertight integrity of the ship which is almost entirely preserved after a collision in the reactor zone.

32. Report on Ship Collision Study Present Situation Survey, by V. Minorsky, George G. Sharp, Inc., November 21, 1975.

Collision research since the SAVANNAH is briefly reviewed. A bibliography of 74 papers is given in four categories: (a) Research (41 papers); (b) Statistics and Probabilities (13 papers); (c) Avoidance (13 papers); (d) Miscellaneous (7 papers). Of these, 14 were translated and 34 abstracted, the abstracts being included in the report.

33. On the Development of Design Criteria for Collision Resistance, by Richard J. Burke, S.U.N.Y. Maritime College, May 11, 1978.

This paper deals with collisions involving a ship carrying a highly poisonous, flammable or explosive cargo which could result in widespread property damage and personal injury in a radius extending far beyond the colliding vessels. A detailed account of the collision between the PACIFIC ARES and the YUYO MARU is given. A summary of research on the mechanics of collision is then presented. This included Minorsky's high-energy collision approach and the rotational effects of an eccentric collision where the amount of energy absorbed by the structure is reduced because some of it is passed to rigid-body rotation. Also discussed Minorsky's added mass value as compared to the actual value which depends on the velocity of the striking ship and depth of penetration. Model testing was next discussed and design variations such as soft bow versus rigid bow, etc. The fact that a ship's side

structure can absorb energy in more than one mode is discussed. Akita's work is briefly examined and the importance at low-energy collision research is expressed. The author identifies a number of factors that are significant with regard to the amount of plastic energy absorbed. These are:

1. Relative strength of side shell plating and weakness of web frames.
2. Position of impact point relative to strong transverse structural members.
3. Shape of the bow of the striking vessel and vertical extent of encounter.
4. Ductility and transition temperature of side shell plating, and the ambient temperature.
5. Strength and type of transverse connections between outer hull and inner hull, if any.
6. Angle of incidence at the point of impact.

The probabilisitc views of collisions are then dealt with and the development of design criteria for collision resistance is examined. The criteria developed would have to evaluate risk. Design criteria which are based on a probabilistic theory must have statistical data. The value of data collected thus far for detailed analysis is limited. On a national level, these criteria would be established by a governmental agency, but such an effort must involve all segments of industry.

While not a highly technical paper, as such, it does give a good picture of the methodology presently being incorporated in ship collision analysis. The difficulty in establishing design criteria is that presently no easy definition of acceptable risk is available. In addition, the criteria should be established on an international scale. The nature of such criteria depends in a large measure on the broadly defined economics of the situation in question. However, the benefits should not be ignored.

34. The Collision Protection of Nuclear-Powered Merchant Ships, Lloyd's Register of Shipping, May 10, 1967.

This paper is a review of the work done on the philosophy of collision protection with a view to assessing the data available to design suitable collision protection for a large nuclear-powered Polar Icebreaker.

35. Tanker Structural Analysis for Minor Collisions, Final Report, M. Rosenblatt & Son, Inc., Report No. CG-D-72-76, December 1975.

This report describes the work accomplished during the course of the project on the Evaluation of Tanker Structure in Collision. The intent of the report is to present the investigations performed in evaluating the phenomena that contribute to the ability of a longitudinally framed ship, particularly a tanker, to withstand a minor collision. A minor collision is defined as one in which the cargo tanks remain intact. The ability to withstand a minor collision is quantified by the total energy that can be absorbed during the collision.

The final output of the study is an analytical procedure and its numerical application for estimating the plastic energy absorbed by longitudinally framed ships when involved in either right angle or oblique collisions. A static analysis is employed. The plastic energy analysis has indicated that the most significant energy-absorbing phenomena are membrane tension in the sideshell (the most important), membrane tension in the deck, shearing of web frames, and plastic bending of the sideshell. Component structures tests and investigations of actual collisions were performed. Parametric analyses are also presented which consist of the numerical application of the plastic energy analysis procedure to six collision incidents in which a 120,000 DWT (and its variants) is struck by a 20,000 ton displacement ship. Another objective of the project was to perform an investigation of non-rigid bows to propose methods of evaluating their significance. Limitations of the procedure are recognized as: (1) the procedure employs static analysis; (2) the striking bows are assessed infinitely rigid; (3) damage to the structure does not extent to the bilge area; and (4) the possibility of the striking bow immediately cutting or punch-shearing the shell of the struck ship was not considered.

36. Ship Collision Dynamics and the Prediction of the Shock Environment for Colliding Ships, by Michael Peter Pakstys, University of Rhode Island, 1977.

The objective of this paper is to develop improved methods to predict the shock environment of two surface ships involved in a collision accident at sea. The collision considered involves the bow of the striking ship colliding at a right angle with the midship bulkhead of a stationary vessel. The collision velocity is assumed to be low enough so that the ship structure deformations are essentially elastic. The technical approach involves integrated analytical and experimental developments. A comprehensive computer program was developed to simulate the ship collision process. Ship model collision tests were performed in a large laboratory water tank.

Shock acceleration values for several values of collision velocity were obtained for right-angle ship collision for two instrumented ship models about the same weight. On the basis of those limited collision tests with floating models, the following conclusions can be drawn on the basis of the observations and the measurements.

1. The hull whipping vibration mode is an important contributor to the shock acceleration of the struck ship. The rigid body acceleration acts only while the colliding ships are in contact.

2. The maximum shock response on the struck ship need not occur at the impact region. In the test case, the peak acceleration at the end bulkheads was 70% higher than that at the center bulkhead where the collision force was acting during the contact with the striking ship.
3. The collision load duration is determined by the deceleration pulse of the striking ship and was found to be independent of collision velocity.
4. The peak acceleration on the struck and striking ship models and the peak collision force were found to be varying essentially linearly with the collision velocity. This indicates that the ship models and the water medium exhibited linear behavior, for the range of collision velocities used.
5. The added mass coefficient for the struck ship vibration corresponded to the theoretical value for high frequency vibration of 0.39 for the specific rectangular section.
6. In the initial collision phase (when maximum shock accelerations occur) the water supporting the floating ships acts essentially as a frictionless medium. Therefore any in-air collision tests where the struck ship is constrained would not give valid results for shock response. The water medium is also slow to dissipate the vibrations of the struck ship since it takes over 100 cycles to reduce the vibration amplitudes by 50%.
7. The tests have provided valid laboratory test data to establish some experimental verification of the analytical approach and computer program results developed by the senior authors for prediction of the shock environment in ship collisions.

3.0 BIBLIOGRAPHY OF DOCUMENTS RELATED TO SHIP COLLISION DAMAGE

The documents contained in this bibliography have been selected from a total of 192 which were reviewed in order to determine their relevance to the problem of ship collision damage prediction. The key documents have been briefly summarized in the Annotated Bibliography of Section 2.3.

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The Ship Design, Response, and Load Criteria Advisory Group prepared the project prospectus, evaluated the proposals for this project, provided the liaison technical guidance, and reviewed the project reports with the investigator:

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SHIP STRUCTURE COMMITTEE PUBLICATIONS

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SSC-272, *In-Service Performance of Structural Details* by C. R. Jordan and C. S. Cochran. 1978. AD-A057212.

SSC-273, *Survey of Structural Tolerances in the U.S. Commercial Ship-Building Industry* by N. S. Basar and R. F. Stanley. 1978. AD-A057597.

SSC-274, *Development of an Instrumentation Package to Record Full-Scale Ship Slam Data* by E. G. U. Band and A. J. Euler. 1978. AD-A059549.

SSC-275, *The Effect of Strain Rate on the Toughness of Ship Steels* by P. H. Francis, T. S. Cook, and A. Nagy. 1978. AD-A059453.

SSC-276, *Fracture Behavior Characterization of Ship Steels and Weldments* by P. H. Francis, T. S. Cook, and A. Nagy. 1978. AD-A058939.

SSC-277, *Original Radar and Standard Tucker Wavemeter SL-7 Containership Data Reduction and Correlation Sample* by J. F. Dalzell. 1978. AD-A062394.

SSC-278, *Wavemeter Data Reduction Method and Initial Data for the SL-7 Containership* by J. F. Dalzell. 1978. AD-A062391.

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SSC-280, *Results and Evaluation of the SL-7 Containership Radar and Tucker Wavemeter Data* by J. F. Dalzell. 1978. AD-A062392.

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SSC-282, *Comparison of Stresses Calculated Using the DAISY System to Those Measured on the SL-7 Containership Program* by H. Y. Jan, K. T. Chang, and M. E. Wojnarowski. 1979.

SSC-283, *A Literature Survey on the Collision and Grounding Protection of Ships* by N. Jones. 1979.

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